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Numerical computation of structures with quasi-brittle materiel under dynamic loading: case study of concrete gravity dam

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Abstract

The present paper deals with a numerical computation using finite element method for concrete structures subjected to dynamic loads, usually of seismic nature the consequences of which are often devastating. In the general equation of dynamic, a law of concrete material behavior taking into account models based on the damage mechanics has been implemented. From a phenomenological viewpoint, the chosen behavior model takes into account the damage caused by the opening of micro-cracks. For numerical application, two dimensional seismic analysis of Koyna gravity dam is performed by using the 1967 Koyna earthquake records. The effects of damage on earthquake response of the concrete gravity dam are studied.

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Keywords: law of behavior, concrete, damage, dynamic loading, cracking, model.

1. Introduction

The simulation of nonlinear problems of damage and fracture processes for quasi-brittle materials, particularly concrete, is the subject of research studies in the field of civil engineering in the goal to serve for vulnerability studies (Lemaitre and Mazars, 1982; Lemaitre and Chaboche, 1985). The phenomena taking part in these processes are often complex and, even in simple cases, the analytical resolution of the problems turns out to

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be, for the least, difficult. To simulate complex structures subjected to static and/or dynamic loads, it is necessary to know the behavior of the material. Concrete is considered as the most used material in the design of structures which may occasionally be exposed to intense dynamic loading, whether of accidental or intentional nature. It belongs to a class of heterogeneous materials with quite complex non-linear behavior. It is a ‘quasi-brittle’ material with a tensile strength significantly low compared to the compression one. Numerous experimental tests showing the aspects of the behavior of this material exists in the literature, such as the impact testing on concrete at high speed (Klepaczko and Brara, 2001; Hervé and Gatuingt, 2002; Hentz et al., 2004) or cyclic loading tension-compression experimental tests (Dubé 1994; La Borderie 1991). These works aims to model the macroscopic behavior and predict damage of the material. Among these models, the J. Mazars model whose principle is based on damage mechanics which is a theory describing the progressive reduction of the mechanical properties of a material due to initiation, growth and coalescence of microscopic cracks. These internal changes lead to the degradation of mechanical properties of the material. The model takes into account the asymmetry of concrete behavior and it considers the cracking in tension and compression failure. This is a model that is generally used for static or pseudo-static systems. The regulatory technical documents for reasons of strength and safety require rigorously that the structures of concrete or reinforced concrete to be sized under dynamic loads especially seismic type. Several studies have been undertaken in this direction to consider structures of damaged concrete subjected to seismic loads (Calayir and Karaton 2005; Omidi et al. 2012; Davenne et al. 2003).We consider in this paper a dam structure designed with concrete subjected to dynamic loading of the seismic type. For dynamic input, the transverse and vertical acceleration components of 11 December 1967 Koyna earthquake are selected. We will consider the hydrostatic effects of the basin per square meter of surface applied to the dam wall, but hydrodynamic effects are not taken into consideration. The effect of the damping coefficient is taken into account in the calculations. The material is based on the isotropic model developed by J. Mazars (1984) in local approach; it is an explicit damage model that can accurately describe the behavior in tension and compression. It also allows reproducing the damage of tension, compression and decrease of stiffness. This model has been implemented in finite element program written in Fortran 90 language, designed to deal specifically with non-linear material modeling. The program is designed to solve the general equation of dynamic, consequently allowing us to calculate the displacements at nodes, strains, stresses and damage at the Gauss integration points. Time integration schemes called explicit are adopted in numerical solution of dynamic equilibrium equations for dam structure with small time step. In particular we adopt a central difference method; it is based on approximation of velocities and accelerations with quotients of finite difference of known values of displacements with regular time step. This method is known conditionally stable, with a very small time interval. We adopt in this work the finite element method, this method is based on a continuous description of matter, it can be applied to numerical simulation of the degradation of quasi-brittle materials for treatment of linear and nonlinear problems.

1. Dynamic equilibrium equations

For dynamic equilibrium of a body in motion, the equation of motion at time station t_n is given as the following expression (1) (Owen and Hinton 1986).

$$M\ddot{u} + C\dot{u} + p_n = f_n \tag{1}$$

where M and C are the global mass and damping matrices respectively, p_n is the global vector of internal resisting nodal forces, f_n is the vector of consistent nodal forces for the applied body and surfaces traction forces grouped together, the body force term $(-M\ddot{u}g)$ due to seismic excitation, is included in the body forces which are taken into account in f_n, $\ddot{u}_n$ is the global vector of nodal accelerations and $\dot{u}_n$ is the global vector of nodal velocities.
Equation of motion (1) can be rewritten by using central difference equation as following (2).

$$u_{n+1} = \left[M + \frac{\Delta t}{2}C\right]^{-1} \left\{(\Delta t)^2\left[-p_n + f_n\right] + 2Mu_n - \left[M - \frac{\Delta t}{2}C\right]u_{n-1}\right\} \tag{2}$$

In order to solve the equation (2) explicitly, the mass matrix M and the damping matrix C are transformed in diagonal matrices. Under these assumptions, equation (2) can be rewritten as a scalar equation (3) (Owen and Hinton 1986; Paultre 2005).

$$(u_i)_{n+1} = \frac{\left[(\Delta t)^2\left\{-(p_i)_n + (f_i)_n\right\} + 2m_{ii}(u_i)_n - \left(m_{ii} - \frac{\Delta t}{2}c_{ii}\right)(u_i)_{n-1}\right]}{\left(m_{ii} + \frac{\Delta t}{2}c_{ii}\right)} \tag{3}$$

The stability of equation (3) is linked to (Δt) a very small time interval. The internal resisting forces using in the numerical program is given by the following expression (4),

$$[p_i]_n = \int_{\Omega} [B_i]^T \tilde{\sigma}_n d\Omega \tag{4}$$

Where $\tilde{\sigma}$ and $[B_i]$ are the effective stress and the global strain-displacement matrix.

2. Constitutive model

In the present work we are going to use the local approach of Mazars's model. It is based on the concept of effective stress developed by Kachanov (1958); the notion of effective stress allows us to distinguish between an original material and a damaged one through a scalar variable D knowing that the condition $0 \le D \le 1$ is representative of the state of degradation of the material. For $D = 0$ the material is considered undamaged, for $D = 1$ the material completely damaged. The expression of the effective stress is given by the following formula:

$$\tilde{\sigma} = (1 - D)\varepsilon \tag{5}$$

Cracks in quasi-brittle materials appear mainly when the material is in tension. The Mazars's model thus considers only positive principal strains. This choice is thus well suited for quasi-brittle materials such as for mortar and concrete. The expression of the equivalent strain with respect to main positive strains is given by

$$\tilde{\varepsilon} = \sqrt{\sum_i \langle \varepsilon_i \rangle_+^2} \tag{6}$$

Where $\langle \varepsilon_i \rangle = (\frac{\varepsilon_i + |\varepsilon_i|}{2})$ and ε_i denote the main strain components $(1 \le i \le 3)$.

2.1. Threshold function

A damage loading function $f(\varepsilon, D)$, depending on damage variable, is introduced. This damage threshold function defines the domain where the behavior is reversible, as long as $f(\varepsilon, D) \le 0$, the damage does not increase. So, for a given state of damage, the loading function is

$$f(\varepsilon, D) = \tilde{\varepsilon} - \kappa(D) \tag{7}$$

Where $\kappa(D)$ is the variable related to the history of the damage; $\tilde{\varepsilon}$ called equivalent strain and depends on main strains ε_i given by the expression (6), such as $\langle \varepsilon \rangle_+ = 0$ if $\varepsilon_i \prec 0$ and $\langle \varepsilon \rangle_+ = \varepsilon_i$ if $\varepsilon_i \geq 0$. Damage D grows when the equivalent strain reaches a threshold $\kappa(D)$ initialized at ε_{D_0}.

$$\text{If } f(\varepsilon, D) = \tilde{\varepsilon} - \kappa(D) = 0, \quad \text{then } \begin{cases} D = D(\tilde{\varepsilon}) \\ k(\dot{D}) = \tilde{\varepsilon} \end{cases} \tag{8}$$

Damage defined by Mazars is split into two parts

$$D = \alpha^{\beta}{}_T D_T + \alpha^{\beta}{}_C D_C \tag{9}$$

The parameter β is representative of shear experiments: it is usually considered as constant ($\beta = 1.05$) (Pierot et al. 2007). D_T and D_C are damage variables in tension and compression respectively. The evolution of damage is provided in an integrated form, as a function of the variable $\tilde{\varepsilon}$:

$$D_{T,C} = 1 - \frac{\varepsilon_{D_0}\left(1 - A_{T,C}\right)}{\tilde{\varepsilon}} + \frac{A_{T,C}}{\exp\left(B_{T,C}\left(\tilde{\varepsilon} - \varepsilon_{D_0}\right)\right)} \tag{10}$$

3. Damage response of Koyna dam

The Koyna concrete gravity dam, 103 m in height and 70.2 m in width shown in Fig.1, is located on the Koyna river in the west of the Indian Peninsula. In 1967, a 6.5 magnitude earthquake shook the region with maximum acceleration measured at the foundation gallery of 0.49 and 0.34 g in horizontal direction normal to the dam axis and in the vertical one, respectively. The time histories (records) of the Koyna earthquake are shown in Fig. 2. Severe damage was found in the form of horizontal cracking observed on both the upstream and downstream faces of the upper part of dam monoliths. In this paper, the nonlinear dynamic analysis of Koyna dam is performed using the concrete model with isotropic damage in local approach. We note that the dam-reservoir interaction is not considered. The mesh of the dam section is shown in Fig. 2 (b). Node ($N313$) is selected to represent the time history graphs of vertical and horizontal movement at the dam crest. The three element integration points (P_{807}, P_{811}, P_{815}) are selected to represent the time history graph of damage.

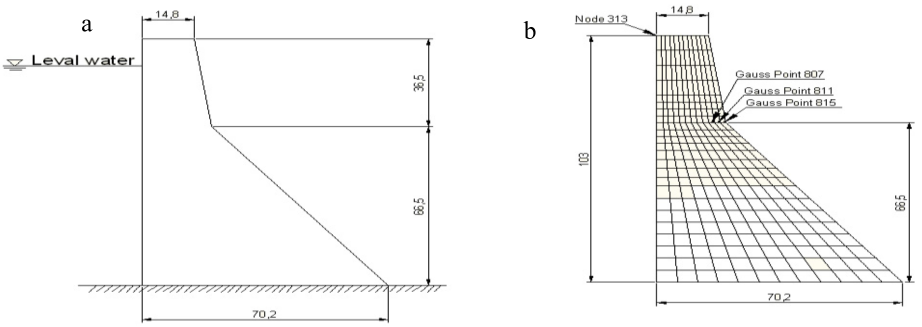

Fig. 1. (a) geometric proprieties; (b) mesh of the dam.

The material properties used in this study are as follow in the table 1.

Table1. Material properties

Elastic modulus	Poisson's ratio	Density	tensile strength	ε_{D_0}	A_t	B_t	A_c	B_c

$E = 31027MPa$	$\nu = 0.2$	$\rho = 2643\,Kg/m^3$	$f_t = 2MPa$	$1.5 * 10^{-4}$	1.0	20000	1.4	1545

The critical viscous damping coefficient used in this study can take three values estimated at 3, 5 and 7%. Integration time step is taken as equal to 0.001 s. The dynamic excitation is by accelerograms whose horizontal and vertical components are the time histories or records of the Koyna earthquake shown in Fig. 2. The effects caused by the earthquake such as displacements, strains, stresses and damage to the gravity dam structure are summarized in graphs that are discussed and compared to results obtained in the literature.

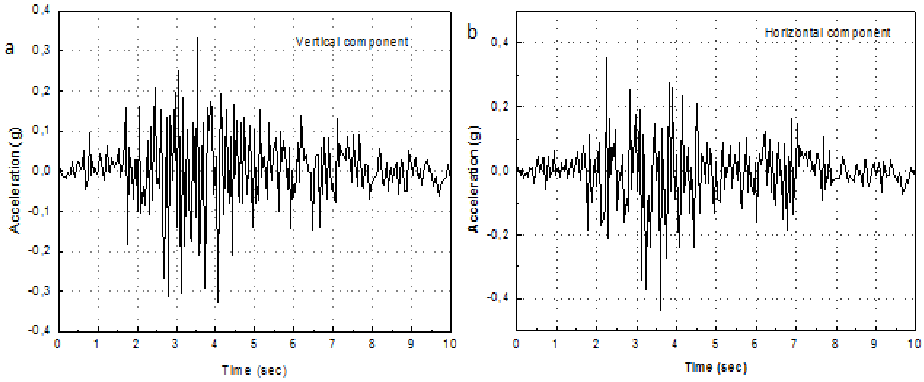

Fig. 2. The Koyna accelerograms. (a) vertical component; (b) horizontal component.

Figure (3) show the time history graphs of the vertical and horizontal displacements of the nodal point (313) located at the crest of the dam

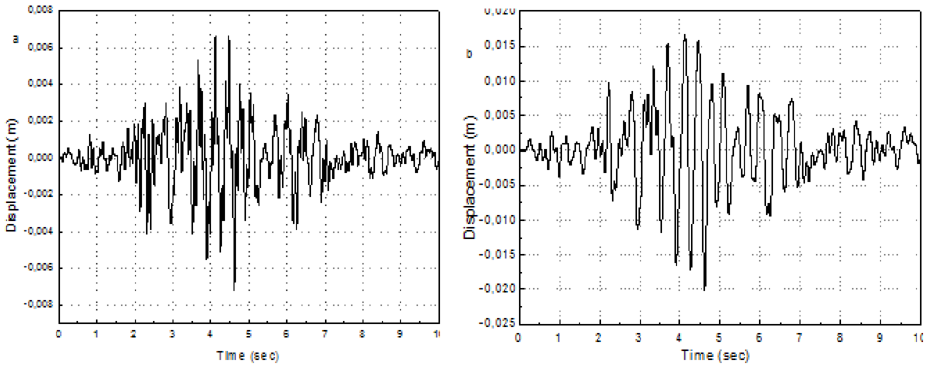

Fig. 3. Time history graphs of the vertical and horizontal displacements of the nodal point 313 at the dam crest.
(a) Vertical displacement; (b) Horizontal displacement.

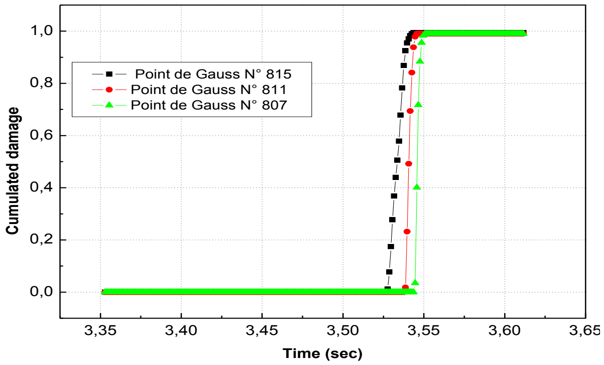

Fig.4. Cumulated damage records at integration points (815, 811 and 807)

4. Discussion of results

In this part, we will report the effects of the concrete damage on the seismic response of the gravity dam. The value of the damping ratio is 5% for the solutions of this calculation example. Fig. 3. show the time history graphs of the vertical and horizontal displacements of the nodal point (313) located at the crest of the dam. We note that the displacements are relatively low during the first two seconds because of low the amplitudes of the excitations. The displacements reach their maximum at 3 s and 4.7 s, 20 mm was recorded at 4.62 s, the maximum displacement value does not correspond to the maximum amplitude of the excitement that is recorded at 3.65 s. The nodal displacements decrease after 5 s. There is no damage during movement where the amplitude is relatively low. Damage were observed (see fig. 4.) in the dam after 3.53 s at the integration point (815) of the element 204, then from 3.54 s at integration point (811) of the element 203 and finally, from 3.54 s at Gauss point (807) of the element 202. It may be noted that the evolution of the damage is mainly concentrated in the time interval where the maximum values of positive and negative displacements occur. The results obtained in our study compared to those of references (Calayir and Karaton 2005 ; Jianwen et al. 2011) are relatively satisfactory.

5. Conclusion

The aim of this study is, firstly to have the response of gravity dam subjected to seismic loading as a time history of the displacements, strains and stresses; secondly to represent the time history of damage evolution in the integration points and to deduce the areas likely to be damaged firstly and how do they develop in the structure. The choice of the method is related to the very small time interval considered. The choice of Koyna concrete gravity dam is due to the fact that many studies have been done on this structure which experienced a devastating earthquake in 1967. The earthquake records are in the form of accelerograms with horizontal and vertical components which are used as dynamic loads. The effect of the damping coefficient is obviously taken into account. Hydrodynamic effects are not considered in this study.

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